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# TERRESTRIAL MAGNETISM.

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# TERRESTRIAL MAGNETISM.

1. The magnetic observations which are at present making by naval officers have for their object the determination of the *amount* and *direction* of the *Earth's magnetic force* in different parts of the globe.

2. The amount of the magnetic force at any point of the Earth's surface may either be measured in *absolute* value, or its *ratio* may be ascertained to the value of the force at another station where its absolute measure is already known. No means have yet been devised for measuring absolute values at sea; consequently, all determinations of the magnetic force on board ships are necessarily of the relative class; these give the ratio, or proportion, which the force at the geographical position in which the ship is at the time when an observation is made, bears to its value at some land station which is included in the same series of relative observations, but where an absolute determination has also been made. Ships are therefore supplied with instruments for both absolute and relative determinations; the latter to be used at sea, and on land at times when the ship is in harbour; the former to be used exclusively on land.

### Absolute *Measurement of the Magnetic Force.*

3. No satisfactory method has yet been brought into practice for the direct absolute measurement in one operation of the *whole* magnetic force of the Earth (called the "total force") at any particular point of its surface. But that portion of the force which acts in a direction parallel to the surface of the Earth (called the "horizontal component") may be measured with considerable accuracy by a process, of which the following brief description may suffice to give a general idea. If a magnet be suspended horizontally by a few fibres of silk, and made to vibrate in the horizontal plane on either side of its position of rest, the square of the number of vibrations in a given time is a measure of the horizontal component of the magnetic force of the Earth, but is also dependent on the individual properties of the magnet employed. These properties influence the time of vibration in two respects: first, by the greater or less magnetic force which the magnet itself possesses; and, secondly, by the effect which the form and weight of the magnet produce on the time of vibration. The latter effect may be eliminated when the moment of inertia of the magnet is learnt; and this may either be calculated by known rules, or may be ascertained experimentally by vibrating the magnet 1° in its usual state, and 2° with its moment of inertia increased by a known amount. The influence of the magnetic force possessed by the magnet may also be eliminated by ascertaining its magnetic moment. This is accomplished by using it to deflect a second magnet similarly suspended in another apparatus. The deflecting magnet is placed at one or more exactly

measured distances from the centre of the suspended magnet, and perpendicular to it. The deflections thus produced, (*i.e.* the angular differences in the positions of rest of the suspended magnet, 1° when influenced solely by the Earth's magnetism, and 2° when in equilibrium between the Earth's magnetism and that of the deflecting magnet at the distances employed,) furnish the *ratio* of the forces exerted respectively by the Earth's force and that of the magnet; and as the *product* of the same two forces is given by the vibrations of the deflecting magnet when suspended as in the experiments first described, the values of either force may be separately ascertained. The influence of the magnetism of the magnet, and of its form and weight, being thus eliminated, a measure is finally obtained of the force of the Earth's magnetism, independent of the individual properties of the magnet employed in the determination.

4. The numerical expression by which the measure of the Earth's force thus obtained is denoted, depends on the units of time, of space, and of mass employed in the measurements and calculation. In conformity with the Instructions published under the authority of the Royal Society, a second of time, a foot of space, and a grain of mass, are the units so employed; and the horizontal component of the Earth's magnetic force has been found, by the observations hitherto made, to vary at different points of the Earth's surface from 0 to about 8·4 of the scale founded on the units which have been specified.

5. Wherever the horizontal component of the force has been ascertained in absolute measure, there also, if the magnetic direction be known, the "total force" in abso-

lute measure is determined; since it consists of the horizontal component multiplied by the secant of the angle which the magnetic direction makes with the horizon. As ships are supplied with instruments by which this angle, called the dip or inclination of the needle, is measured, the observations on land, when the ship is in harbour, give determinations of the total force, which serve as *base determinations*, to which are referred the *relative* results obtained at sea in the passage from one station of well-assured *absolute* determination to another;—a practice corresponding to that which prevails in determinations of longitude, where stations of well-assured longitude are taken as *base stations*, to which intermediate observations are referred. The total force of the Earth's magnetism, expressed in the scale in which the British units already referred to are employed, has been found to vary at different points of the Earth's surface where observations have hitherto been made, from about 6·4 to 15·8. Before the practice was adopted of determining absolute values, various relative scales were employed, not always commensurable with each other. The one most generally used (and which still continues to be very frequently referred to), was founded on the time of vibration of a magnet observed by M. de Humboldt about the commencement of the present century, at a station in South America where the direction of the dipping-needle was horizontal; a condition which was for some time erroneously supposed to be an indication of the minimum of magnetic force at the Earth's surface. From a comparison of the times of vibration of M. de Humboldt's magnet in South America and in Paris, the ratio of the magnetic force at Paris to what

was supposed to be its minimum was inferred; and from the result so obtained, combined with a similar comparison made by myself between Paris and London in 1827 with several magnets, the ratio of the force in London to that of M. de Humboldt's original station in South America has been inferred to be 1·372 to 1·000. This is the origin of the number 1·372, which has been generally employed by British observers, not furnished with the means of making absolute determinations, to express the value of the magnetic force at their base station, viz., London. The essential disadvantage, however, under which any relative scale of the nature referred to labours, is, that the magnetic force of the Earth has been found to be subject to secular variations, so that at no one spot on the surface of the globe can the intensity be assumed to remain constant, and thus to afford a secure unvarying basis for such a scale; whereas by absolute measurements, we are not only enabled to compare numerically with one another the results of experiments made in the most distant parts of the globe, with apparatus not previously compared, but we also furnish the means of comparing hereafter the intensity which exists at the present epoch, with that which may be found at future periods. It is probable from these and other considerations, that the employment of mere relative scales will shortly be entirely superseded by the general adoption of a scale in which the value of the force is expressed in terms of a fixed and unchanging unit.

6. The instrument with which the absolute value of the horizontal component of the force is measured is called the Unifilar Magnetometer; its description, and that of the process by which results are obtained with it, are given in

Appendix No. 1. A tolerably practised observer will complete the process by which a measure of the absolute horizontal force is obtained in about two hours, including the time required for setting up and adjusting the instrument. It is desirable that there should be at least five or six repetitions at places which are to serve as base stations; and also, as a spare magnet is always supplied, that both magnets should be employed. There are certain constants, [such as the moment of inertia of the magnet and stirrup in which it rests, the change which the magnetic moment of the magnet undergoes from an alteration of one degree of temperature, and the coefficient in the correction required for an increase of force which the magnet, in certain positions in which it may be used, may receive by induction from the earth,] which have to be determined for each magnet once for all, and require for their determination apparatus which is not afterwards needed: these constants have hitherto been usually determined at Woolwich before the instrument is put into the hands of the officer who is to use it elsewhere.

Relative *Measurements of the Magnetic Force.*

7. These are the observations which are made at sea, to determine the ratio of the total force in the geographical position of the ship at the time when the observation is made, to its value at some base station where the instrument has been landed and used in precisely similar observations to those made on board ship. The instrument is the well-known apparatus devised by Mr. Fox, which has contributed more to a knowledge of the geographical distribution of terrestrial magnetism than any

other recent invention. The following brief description may serve to give a general idea of the apparatus and of the mode of obtaining results with it, more full directions for its use being given in Appendix No. 2. It consists of a dipping-needle and graduated circle, differing little from the accustomed form of an Inclinometer, except that the needle is supported by the ends of the axle, which terminate in cylinders of small diameter working in jewelled holes. A small grooved wheel is carried on the axle, and receives a thread of unspun silk, furnished at each extremity with hooks to which small weights may be attached, for the purpose of deflecting the needle from its position of rest in the magnetic direction, and causing it to take up a new position, in which it is in equilibrium between the opposing forces of the Earth's magnetism and of the deflecting weight. The weight being constant, and the magnetism of the needle assumed to be so, the intensity of the Earth's magnetic force in different localities is inversely as the sines of the angles of deflection. For greater accuracy, several constant weights are employed on each occasion; and each weight is successively attached to each of the two hooks, a mean being taken of the deflections on either side of the position of rest. The apparatus when used at sea is placed on a gimball table, by which the motion of the vessel is greatly counteracted; and when the weather does not permit the manipulation of the weights, deflecting magnets are substituted, the operation of which may be understood from the detailed instructions in Appendix No. 2. With the gimball table as recently constructed, it is found that but very few days occur in which the

angles of deflection, either with weights or deflectors, cannot be satisfactorily ascertained by a careful observer. It is necessary that a spot should be selected for the observations to be made on board ship, which should have as little iron as possible within 5 or 6 feet of it; and that the instrument should always be used in the spot so selected. The mode of investigating and of eliminating (when these precautions are taken) the influence on the results of the iron contained in the ship is explained in Appendix No. 4. It must be carefully borne in mind, that the inverse proportionality of the sines of the angles of deflection to the variations of the earth's magnetism, is only true when the magnetism of the needle has not varied; and although the needles made by Falmouth artists, under Mr. Fox's own superintendence, have generally proved most remarkable in preserving their magnetism unchanged for years and in all climates, it is desirable that reference to a base station should be made as often and with as short intervals as may be convenient; and evidence must always be furnished that the magnetism of the needle has not changed in a certain interval, before the relative determinations made during that interval can have weight. The more frequently references are made to base stations at which the value of the magnetic force is known, the less danger exists that the labour bestowed on observations at sea will prove unproductive; and the more stations are multiplied which afford opportunities of such reference, the greater become the facilities for accurate determinations at sea.

*Direction of the Earth's Magnetic Force.*

8. The direction of the Earth's magnetic force undergoes every possible variation at different parts of the Earth's surface. For the purpose of determining and representing this direction, it has long been customary to refer it to two planes—the horizontal and the vertical planes—and to take the geographical north as the zero of the horizontal plane, and the horizontal line as the zero of the vertical plane. The *declination* (or *variation*, as it is more usually called by naval men) is the angular difference, measured on the horizontal plane, between the direction of the north end of a magnet or needle and the geographical north point; and the *inclination* (or *dip*, as it is frequently called) is the angular difference, measured on the vertical plane, between the direction of the same north end of a magnet or needle and the horizontal zero-point. (The north end of a magnet here spoken of is that end which in Europe points towards the north, and dips below the horizon.) The declination is called West, if the direction of the north end of the magnet or needle is to the west of the geographical north, and is reckoned from 0° to 180°, passing from North through West to South. In like manner, the declination is called East, if the direction of the north end of the needle is to the east of the geographical north, and is reckoned from 0° to 180°, passing from North through East to South. The positive and negative signs are also sometimes applied instead of the terms West and East, in which case + signifies West, and − East Declination.

The Inclination is counted positive, or has the sign

*plus* prefixed, when the north end of the needle inclines below the horizon; and is counted negative, or has the *minus* sign prefixed, when the north end of the needle inclines above the horizon. Sometimes, instead of the signs + and −, the terms North and South are used, in which case North Inclination or Dip is when the north end of the needle dips below the horizon, and South Inclination or Dip is when the south end of the needle dips below the horizon. Thus an Inclination of − 30° is equivalent to 30° South Dip.

9. The Declination is measured by the azimuth compass, an instrument too well known to naval officers to require any description here, or any directions for the method of observing with it either on land or at sea. As now made, under the superintendence of Captain Johnson, R.N., and on the plan recommended by the Committee for the Improvement of Ships' Compasses, the azimuth compass in the hands of a careful observer, attentive to the practical rules published by the Admiralty for ascertaining the deviations of the compass caused by the iron of a ship, will give results, both at sea and on land, which leave little to be desired. The use of the dipping needle, which measures the inclination, not being so generally familiar to naval officers, full directions for its employment are given in Appendix No. 3.

### *Local Attraction.*

10. It has been found that the results of magnetic observations, whether of the declination, inclination, or of the intensity of the magnetic force, are liable to be influenced by local attraction proceeding from the rocks or soil in the

vicinity of the instrument, and particularly so at stations where the rocks are of igneous character, such as traps, basalts, granites, &c. As a precautionary measure, therefore, magnetical instruments should always be used on stands which raise them 3 or 4 feet above the ground; and those stations are to be preferred of which the geological character is sedimentary or alluvial. Stations of igneous character, though less eligible for obtaining results which show the correct magnetical elements corresponding to the geographical position of the station, may nevertheless be serviceable as stations of comparison between the land and sea instruments; but for this purpose it is essential that the different instruments to be compared should be used precisely on one and the same spot, in which case the local attraction may be supposed to be a constant quantity. And if the station be one frequently resorted to by vessels from which magnetic observations are made, it is desirable that the spot should be susceptible of a definite and well-recognisable description.

At sea, from the quantity of iron which a ship contains, it is scarcely possible that its influence on the instruments should be altogether avoided; but from the circumstance that the greater part of the most influential iron is in fixed positions in the ship, it has been proved by sufficient experience, that by a proper selection of the place in which a magnetic instrument is used on board ship, and by a certain process of observation (repeated whenever the ship has undergone any considerable changes of geographical position), the influence of her iron is susceptible of a sufficiently approximate calculation, and of being eliminated accordingly.

The importance, and in some degree the novelty, of this part of the subject has made it appear desirable that it should be treated somewhat fully in Appendix No. 4.

*Summary of the Observations to be made.*

11. An officer, therefore, who purposes to make magnetic observations, or to cause them to be made on board his ship, has to attend to the following points:—He must take care that he obtains the instruments some days before the ship is ready for sea, in order that he may assure himself that they are all complete, and that, if inexperienced in their use, he, or the observer whom he selects, may have some preliminary practice with them. He will then have to determine the constants, index corrections, &c. (unless these shall have been furnished with the instruments), and to make the observations required for a base station, with the needles which are to be employed in the relative determinations of the magnetic force and dip at sea. Positions will then have to be selected on board for the standard compass, and for Fox's apparatus, and the pillar for the one, and the gimball stand for the other, fitted accordingly. When the ship is ready for sea, the observations which are directed in the Admiralty Instructions for ascertaining the deviations of the compass caused by the iron of the ship are to be made on board; and when the ship is swung round for this purpose, the deviations of the dip and of the force must be also observed, on the sixteen, or at least on the eight, principal points of the compass, with Fox's apparatus used at the spot selected for it.

This completes the preparations to be made before the ship's departure. Whilst at sea, the observations of dip

and intensity described in Appendix No. 2, as well as those of the variation by the standard compass, should be made daily, whenever the weather and other circumstances permit. Whenever the ship is in harbour, and time and opportunities are suitable, it is desirable that the instruments should be taken on shore, to a spot selected as least likely to be influenced by any local attraction; and that the declination, inclination, and absolute horizontal force should there be determined, and the comparative observations made with Fox's apparatus. If the ship has materially changed her geographical position since the last occasion when the deviations were ascertained, or if changes have been made in her equipment by which the deviations may have been affected, it is desirable that the process for their examination should be repeated; and lastly, the harbour observations here described should not fail to be repeated whenever the ship finally returns to England.

*Record and Transmission of the Observations.*

12. Blank forms are supplied for the entry of observations of all classes, and for the first or uncorrected calculation of those which require that process to be gone through at the time. It is desirable that the forms should be filled up in duplicate, and that one copy should be retained, and the other sent to England from time to time, as soon as circumstances make it convenient. On their arrival they should be immediately examined, and any suggestion to which they may give rise communicated at once to the observer.*

* This has hitherto been done on all occasions when practicable, and it is very desirable that it should always continue to be done.

*Application of the Results.*

13. The observations when thus received require that the several corrections arising from the influence of the iron, the variations of temperature, the changes in the magnetic force of the magnets, and from various other sources, should be sought out, computed and applied, and the true or corrected results finally derived. These form the materials from which it is intended to construct maps, showing the variations of the magnetic force, and of the magnetic direction in its two co-ordinates of inclination and declination, corresponding to the present epoch, over the whole surface of the globe. The variations of the three elements are shown on these maps, by lines connecting, for example, in the maps of the magnetic force, those points, where the intensity is observed to be the same;—in the maps of the inclination, those points where the inclination is observed to be the same;—and in the maps of the declination, those points where the declination is observed to be the same. These lines are known by the names of Isodynamic, Isoclinal, and Isogonic lines. The Isogonic lines, which form the maps of the declination (or variation charts), have a direct practical importance and value in navigation, which in a notice addressed to naval officers needs not to be dwelt on. In theoretical respects, the Isodynamic and Isoclinal lines are not less essential; the three form the basis of a systematic view of terrestrial magnetism, as it manifests itself to us on the surface of the globe.

The mode in which the results are made to contribute to the formation of these maps is the following:—The

results of the three elements finally corrected are entered, each in its proper geographical position, on maps on a large scale, severally appropriated to the force, the inclination, and the declination. Each result has a small characteristic mark denoting the observer. When any portion of the globe is sufficiently covered by the results of observations in proper distribution, the isophænomenal lines are drawn for that portion of the globe in correspondence with the observations, with a free hand, but with a careful judgment, aided occasionally by a process of calculation which it is not necessary here to describe. From these maps tables of double entry are formed, having the latitude at the side, and the longitude along the top of the page, and the values of the magnetic elements corresponding to the several latitudes and longitudes are placed at the points of intersection. By proper care in the process, the step of forming the tables from the maps need involve no additional uncertainty whatsoever. Maps and tables thus prepared will, when completed, form an experimental theory of terrestrial magnetism, in which the facts of nature will be shown with greater or less exactness, in proportion as the observations are numerous, correct, and suitably distributed, and as they are more or less correctly represented in the maps. Mathematical formulæ, based on general mathematical views, having numerical coefficients of which the values are derived from these maps, may also serve for the computation of the magnetic elements at any geographical position on the surface of the globe; and if the points taken from the maps to serve as the basis of the numerical values of the coefficients are sufficiently numerous,

and have a proper distribution over the surface of the globe, and if the formulæ are carried to a sufficient number of terms, it may be expected that the elements computed from them will have the same degree of exactness as the maps from which their coefficients are taken.

It may be natural at this stage to inquire what prospect exists of being able to complete a work of this magnitude within a reasonable time; and to this question a more satisfactory reply can be returned than may perhaps be generally anticipated. Nearly three-fourths of the surface of the globe being covered by the ocean, it is chiefly by naval surveys that the materials for such a work can be collected. By the zealous and unwearying assiduity of British officers, acting under the sanction and with the approval of the Lords Commissioners of the Admiralty, and in some instances in expeditions specially appointed for the purpose, magnetic observations designed expressly for the object above-mentioned, and conducted upon a uniform system, have been extended, since their commencement in 1839, over nearly all the accessible parts of the ocean.

Of these surveys, the results of some have been already deduced and published in the Philosophical Transactions, the expense of publication having been borne conjointly by the Government and by the Royal Society; the results of others are undergoing the process of calculation and arrangement for publication; and in a third class, more numerous than either of the other two, the observations themselves are still in progress. In the class first referred to, viz. surveys in which the observations have been completed and the results deduced and published, may be

named a portion (about the half) of the observations of the Antarctic expedition under Sir James Clark Ross: those of the expedition under Lieutenant Moore, R.N., and Lieutenant Clerk, Royal Artillery, also to the Antarctic Ocean; of Captain Sulivan, from England to the Falkland Islands and back; of Sir Edward Belcher, (in H.M.S. Sulphur,) on the north-west coast of America, and in the Pacific and Indian Oceans; of Lieutenant Alexander Smith, R.N., and Lieutenant Dayman, R.N., in voyages between England and Van Diemen Island. In the second class, viz. surveys completed and in progress of reduction but not yet published, may be enumerated the remaining portions of the observations made in Sir James Clark Ross's Antarctic expedition; a small but valuable collection by the Niger expedition; another by Sir Robert Schomburgk in Guyana; two series on the coast of New Holland, one by Captain Wickham, and the other by Lieutenant (since Captain) Stokes; the observations made in a special expedition to Hudson's Bay and back by Lieutenant Moore; and two extensive series, one by Captain Shadwell, in the hydrographical expedition of Captain Blackwood to Torres Strait and round New Holland; and one by Sir Edward Belcher in H.M.S. Samarang, in the Indian and Chinese Seas.

Amongst the observations now in progress may be named those of the expeditions to the Arctic Polar Sea under Sir John Franklin and Sir James Clark Ross; of the hydrographical surveying expeditions of Captain Barnett in Bermuda and the West Indies; of Captain Graves in the Mediterranean; of Captain Kellett in the Pacific; of Captain Bayfield in the Gulf and River St. Lawrence;

of Captain Owen Stanley in Torres Strait and the coasts of New Guinea; of Lieutenant (now Commander) Moore in the Pacific and Behring's Strait; and of Captain Stokes in New Zealand. To these must be added a very valuable magnetic survey still in progress amongst the islands of the Indian Archipelago by Captain Elliot of the Madras Engineers, at the expense of the East India Company.

When it is borne in mind that several of the above-named surveys include periods of three or four years, and in some instances not only determinations at the several ports and harbours which may have been visited, but also daily observations (weather permitting) of the three magnetic elements at sea in passages from port to port, the accumulation of materials, and their already extensive distribution over the surface of the globe, may in some degree be judged of. No part of the globe has yet however been considered so far completed, that its magnetic curves have been finally drawn, or the tables of the magnetic elements corresponding to geographical positions finally derived from them. The results of each individual series are computed and published as soon after they have been received in a complete state, as can be accomplished by the establishment at Woolwich, which is very limited in comparison with the duties it endeavours to perform. The magnetic lines indicated by each series are also provisionally drawn; but the final co-ordination of the different series, and their combination with the results of the magnetic surveys carrying on at the same time by governments and individuals in various parts of the remaining fourth of the globe which is occupied by

land, is deferred until the accumulation of materials in the more frequented portions shall appear sufficient for the purpose, and until in the less frequented portions there shall be no immediate prospect of any further considerable accession. The final period at which the work may be completed cannot but be accelerated by the step which the Lords Commissioners of the Admiralty have taken, in desiring the present notice to be drawn up, and in holding out inducements to naval officers of professional and other advantages, as a recompense for what may in some respects be regarded as extra-professional services. With due hesitation in expressing an opinion on what is future, and contingent on many circumstances, it may be stated that hopes are entertained that the year 1851 may see the work completed.

In prosecuting a work of this general and purely experimental character, unconnected with hypothesis of any sort, the phenomena of all parts of the globe must be viewed in the abstract as possessing an equal importance; and it does not appear desirable, therefore, to name any one of the lines, whether isogonic, isoclinal, or isodynamic, as deserving of special attention in preference to others. There is one direction, however, which may be safely given, and which it may be well to remember at all times, viz., that "the value of each new station is directly proportional to its distance from those where observations have already been made;" and in this point of view it may be useful to notice, that up to the present time fewer observations have been made in the Pacific than either in the Atlantic or the Indian Oceans.

# APPENDIX No. 1.

## Description and Use of the Unifilar Magnetometer.

The Unifilar Magnetometer consists of two parts—an apparatus for deflection, and an apparatus for vibration: these correspond with the two parts of the process by which the absolute horizontal force is determined; the experiments of deflection consist in observing the angular deflection of a suspended magnet produced by the influence of a second magnet, which is placed on a support at one or more known distances from the suspended magnet, and in a line drawn from its centre perpendicular to its direction: the experiments of vibration consist in suspending the magnet which was used as the deflecting magnet in the experiments of deflection, and observing its time of vibration. By the first part of the process (or the experiments of deflection) we obtain the *ratio* of the magnetic moment of the deflecting magnet to the Earth's horizontal magnetic force at the place of observation; the latter being to the former as 1 to the sine of the angle of deflection multiplied by half the cube of the distance employed;—or if $m$ denote the magnetic moment of the needle, X the Earth's horizontal force, $r$ the distance apart of the centres of the magnets, and $u$ the angle of deflection, the expression is—

$$\frac{m}{X} = \tfrac{1}{2} r^3 \sin u.$$

By the second part of the process (or the experiments of vibration) the *product* of the same two qualities is obtained: being the quotient of a constant, which we may call $\pi^2$ K (see p. 38), divided by the square of the time of vibration: or if T be the time of vibration,

$$m\,X = \frac{\pi^2 K}{T^2}$$

The values of $m$ X and $\frac{m}{X}$ being known, those of $m$ and X may be obtained separately: for if we call $m$ X $= \alpha$ and $\frac{m}{X} = \beta$, $m$ (the magnetic moment) $= \sqrt{\alpha\beta}$, and X (the horizontal component of the Earth's magnetic force) $= \sqrt{\frac{\alpha}{\beta}}$.

### *Deflection Experiments.*

1. Place the tripod base and copper box upon the stand, and screw on the torsion tube; form a thread capable of carrying the smaller

magnet, *i. e.*, the magnet of 3·00 inches in length (a single fibre of silk is generally strong enough to support it); affix the deflecting rod, and the telescope and scale; level the base circle very correctly, suspend the 3-inch magnet, and raise it until it is in the same horizontal plane with the deflecting magnet when resting on the supports.

2. Place the 3·67-inch (or deflecting) magnet on the graduated support to the west of the suspended magnet, with its centre at the distance determined upon, and with the north end towards the East. Turn the telescope in azimuth until the central division of the scale attached to the telescope is on the vertical wire; write down the readings of the verniers, and the height of the thermometer placed near the deflecting magnet.

3. Reverse the deflecting magnet, placing the south end where the north was, and bringing its centre precisely to the same distance from the suspended magnet as before. Turn the telescope until the central division of the scale is again on the vertical wire, and write down the readings, together with the height of the thermometer.

4. Repeat these observations by reversing the deflecting magnet again and again, until, judging by the agreement of the several results, sufficient accuracy appears to be obtained. Two or three repetitions will generally be found to suffice.

5. Place the deflecting magnet at the same distance on the opposite support, and repeat the same series of observations, commencing as before with the north end of the magnet towards the East. Take a mean of the readings of the circle in the 1st and 3rd positions of the deflecting magnet, and another mean of the readings in the 2nd and 4th positions; half the difference of these means will be the angle $u$ corresponding to the distance $r$. The distance $r$ should be such as to produce a sufficiently large deflection in the suspended magnet. At Woolwich, where the value of the horizontal component of the terrestrial force is 3·7, the deflecting magnets of 3·67 inches in length, when recently magnetized, will usually produce a deflection of about 10°, when the distance from centre to centre of the magnets is 1·3 foot. But with a constant distance the deflection would increase in localities where the horizontal component is less, and diminish where it is greater: the deflection would also be diminished if the deflecting magnet lost any portion of its original charge. It is not desirable that the deflection should be less than 6°.

When the distance required to produce a sufficient deflection is less than five times the length of the deflecting magnet, the amount of the deflection is liable to be influenced by the distribution of the magnetism in the magnets employed, which does not follow the same law in all magnets. In such cases it is necessary to employ two or more distances

for the purpose of eliminating this effect. If two distances are employed, they should be to each other in the proportion of 1 to 1·3 nearly; or for magnets of the specified length and strength, 1 foot and 1·3 foot may generally be found convenient and suitable distances, in which case the lesser distance should be denoted by $r$, and the greater by $r_{,}$, the corresponding deflections being $u$ and $u_{,}$.

Where two distances are employed, no alteration is required in the experiments of vibration; but in those of deflection it will be found convenient to adopt the following routine:—

1. Observe the angle of deflection with the north end of the deflecting magnet alternately to the east and to the west (with the proper number of repetitions), the magnet being placed on the eastern arm, and at the least of the two distances.

2. Go through the same process with the magnet still on the eastern arm, but at the greater of the two distances.

3. Repeat No. 2 on the western arm, and

4. Repeat No. 1 on the western arm, the order of the distances in Nos. 1 and 2 being inverted in Nos. 3 and 4.

If the distance required to produce a sufficient deflection should be less than four times the length of the deflecting magnet, it may be desirable to obtain three or more values of $u$ ($u$, $u_{,}$, $u_{,,}$, &c.) at three or more distances ($r$, $r_{,}$, $r_{,,}$, &c.); in such case it is convenient for the calculation that the distances should have a common difference; as, for example, (in decimals of a foot) ·9, 1·1, and 1·3; 1·1 being supposed to be the distance ordinarily employed when time and circumstances will not permit more than a single distance; and the other two distances to be employed in addition when there may be full leisure for the purpose.

*Vibration Experiments.*

1. For these experiments the tripod stand carries a table top, which is furnished with an azimuthal motion, and can be clamped to the tripod. A telescope with a scale attached to it for measuring the arc of vibration is fixed to the table, as is also a rectangular box of wood, with a glazed side, furnished with a tube for the suspension of the 3·67 inch (or deflecting) magnet. The table must be levelled by means of the foot-screws, and turned in azimuth until the mirror attached to the stirrup in which the magnet is supported reflects in the telescope the centre division of the scale attached to the telescope. The magnet rests during the experiments of vibration in a stirrup carrying a mirror, and is suspended by a silk thread of which the ratio of the torsion force to the magnetic directive force must be ascertained, by turning the index of the torsion circle 90°, first in one direction and then in the other, and taking the mean of the corresponding angles through which the magnet

is deflected. Then if H denotes the co-efficient of the torsion force, and F the Earth's directive force,

$$\frac{H}{F} = \frac{\text{the mean angle (in minutes of arc)}}{90^\circ - \text{the mean angle (in minutes of arc)}}.$$

2. The magnet, being at rest, must be made to vibrate in small arcs by means of another magnet, and the time of 300 vibrations observed in the following manner:—The arc of vibration being about 60 divisions (or minutes) on either side of the central division, note the time when the central division crosses the vertical wire of the telescope, passing from left to right; do the same when the central division passes from left to right for the third, fifth, seventh, ninth, and eleventh times, corresponding to the completion of vibrations 4, 8, 12, 16, 20, and 24. This will give the approximate interval of time in which 20 vibrations are performed; and will indicate to the observer, without requiring him to count the intermediate vibrations, when he should be prepared to observe the completion of the 60th, 120th, 180th, 240th, and 300th vibrations. At the 300th vibration he should recommence taking the time of the 300th, 304th, 308th, 312th, 316th, 320th, and 324th vibrations. He will then have seven partial results for the time in which 300 vibrations are performed, viz.—

| | | | | | |
|---|---|---|---|---|---|
| 0 | to | 300 | 12 | to | 312 |
| 4 | to | 304 | 16 | to | 316 |
| 8 | to | 308 | 20 | to | 320 |
| | | | 24 | to | 324 |

of which seven partial results he should take the mean.

The temperature of the magnet should be observed by a thermometer placed in the box with the magnet, before and after the experiments by which its time of vibration is determined.

The data required from the observer on each occasion are the following:—The mean time of 300 vibrations, and the particulars from which it is derived (or the partial results); the commencing and concluding arcs of vibration; the temperature of the magnet; the rate of the chronometer by which the times are observed; and the ratio of the torsion force to the Earth's directive force, or $\frac{H}{F}$.

If, then, T′ is the observed time of a single vibration, and T the corrected time, the corrections may be computed by the following formula:—

$$T = T'\left(1 + \frac{H}{2F} - \frac{a\,a'}{16} - \frac{x}{86400}\right)$$

in which $a$ and $a'$ are the commencing and concluding arcs in parts of radius, and $x$ the rate of the chronometer. When the commencing arc

of vibration is as small as above directed, the correction for it may be disregarded, except when great accuracy is sought.

It is desirable to commence the observations for the determination of the absolute horizontal force with the experiments of vibration; then to make the series of deflection experiments; and then to repeat the experiments of vibration. The experiments of deflection and vibration thus described will complete a single determination. There should be three such determinations with each of the 3·67-inch magnets at a base station; and all should not be made on the same day, lest it should happen to be a day on which the magnetism of the Earth is disturbed.

The constant $\pi^2$ K (page 22) is obtained from $\pi$, denoting the ratio of the circumference of a circle to its diameter, and K the moment of inertia of the magnet, including the stirrup (and its appendages) in which the magnet rests during the experiment of vibration. To determine the moment of inertia, the magnet, stirrup, &c. is vibrated a second time with the addition of a metal ring, of which the exterior and interior diameters, as well as the weight, are accurately known. If $r$ and $r'$ denote the exterior and interior radii, (in decimals of a foot,) and $w$ the weight, (in grains,) the moment of the inertia of the ring is

$$K' = \tfrac{1}{2}(r^2 + r'^2)\,W;$$

and if T denote the time of vibration without the ring, and T′ the time of vibration with the addition of the ring, the moment of the inertia of the magnet and stirrup in the vibrations without the ring is given by the formula,

$$K = K'\left(\frac{T^2}{T'^2 - T^2}\right).$$

As this determination requires several repetitions, it is usually made before the instrument is put into the hands of the observer; but as its value must be found afresh if any alteration be made at any time in the stirrup or its appendages, a ring is always supplied for the use of the observer.

If the temperature of the magnet be not the same in the experiments of deflection and vibration, the value of $m$X as observed at the time of the experiments of vibration, must be reduced to that which it had at the time of the experiments of deflection. For this purpose it is necessary to know the amount of change in the magnetic moment of the magnet occasioned by one degree of temperature. This is called the temperature coefficient, and is usually denoted by $q$. As its determination requires apparatus with which ships are not supplied, it has been customary to furnish it with the instrument. Then if $t$ and $t_o$ be the temperature of the magnet at the times of deflection and vibration

respectively, $m$ X derived from the experiments of vibration, becomes when corrected to the temperature of the experiments of vibration;

$$m \text{ X } \left[1 + q\ (t - t_o)\right]$$

The absolute horizontal force determined by the foregoing process will finally require a very small correction, on account of the circumstance, that the magnetic moment of the deflecting magnet is not strictly identical in the different positions in which it is placed in the experiments of deflection and vibration, as it is perpendicular or nearly so to the magnetic meridian in the first case, and coincides with it in the other. In the first case, the magnetic moment is that proper to the bar itself; in the second case it is augmented by the inducing action of the earth. The coefficient for this correction requires a separate apparatus for its determination, and the correction may be applied to the results when finally re-computed at Woolwich, as it requires no special data to be furnished by the observer.

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## APPENDIX No. 2.

### Directions for using Mr. Fox's Apparatus for observing the Magnetic Inclination and Force.

#### I.—General Remarks.

In fixing the gimball table, it is convenient that it should be so arranged that when the apparatus is placed on it, the zero divisions of the horizontal circle should coincide with the fore and aft midship-line of the ship.

In preparing for an observation at sea, the circle should be turned in azimuth until the vernier of the horizontal circle shows an angle with its zero, corresponding with the difference between the magnetic meridian and the course which the ship is steering. The plane of the circle will then coincide with the magnetic meridian, when the ship is steadily steered. When from circumstances of weather, &c., the steerage is difficult, an assistant is required to indicate to the observer the times when the ship is steady on her course.

The apparatus is usually furnished with three or four needles, one of which is intended to be used on shore for the determination of the true inclination (when no special instrument is provided for the purpose), by the process subsequently described, Appendix 3, in which the poles are reversed. The other needles, which are intended for the intensity, are never to have their poles reversed, and care is to be taken not to place them inadvertently near other magnets or iron. Besides the needles,

two other magnets are supplied to be used as deflectors. In replacing the needles and deflectors in the travelling box, care should always be taken that the poles of each occupy the places marked for them in the box.

It is desirable to use always the same needle at sea, and to keep it always mounted, clamping it before it is put away for the day; but in case of its undergoing any considerable deterioration from use or accident, one of the other intensity needles may be substituted for it.

When changing the needles at a land station, be very careful not to injure the jewels, or the terminations of the axles of the needles; when a needle is changed it is desirable to hold it chiefly by the grooved wheel; the pivot should first be put into the outer jewelled hole, and the opposite pivot should be carefully guided into the hole at the back whilst the bracket is screwed up.

With respect to the constant weights, it is desirable that the smallest angle of deflection produced by any of the weights employed should not be less than 30°. On account of possible instrumental irregularities it is usual to employ more constant weights than one, with differences between each of half a grain, (as for example, 2 grains, 2½ grains, 3 grains, &c.). Great care is taken that all the weights which have the same nominal value should be equiponderant, but it is desirable if possible to preserve the same identical weights throughout the whole observations of the same relative series.

## II.—Observations at Sea.

### A.—*Inclination.*

1. *Direct Observation.*—The instrument having been placed on the gimball stand and levelled, and the plane of the circle made parallel to the magnetic meridian, with the face of the circle towards the East, release the needle, which will immediately take approximately the direction of the inclination; rub gently the centre pin at the back with the ivory disk, and read off successively the divisions of the limb indicated by the two ends of the needle; note the readings, which will be +, or positive, when the North pole of the needle dips, and —, or negative, when the South pole of the needle dips: repeat the observation three times, turning the bracket which supports the needle a small quantity between each observation, and being careful to rub the centre pin at the back with the ivory disk whilst reading off. The bracket is turned by means of the screw heads at the back of the circle, and the object of turning it is to cause the ends of the axle of the needle to have different points of bearing on the jewels in each observation.

In reading the divisions on the limb, be careful always to bring the

division nearest to the needle to coincide with the corresponding division of the second graduated circle immediately behind it, by which means parallax is avoided.

The mean of the three observations or six readings above described is the apparent inclination by direct observation with the face East.

2. *Observation with Deflectors.*—Having made the preceding observation, screw in the deflector N (or the north pole of a second needle used as a deflector), and adjust the circle at the back by means of its verniers, so that the deflector may be 40° on one side of the division which in the preceding process (§ 1.) was read off as the direct observation with the face East. The needle will then be repelled, and will settle on the opposite side of the dip; read off (always whilst rubbing with the ivory disk) the divisions indicated by the two ends of the needle. Repeat the observation three times, altering the bearings of the ends of the axle between each observation as before directed. Turn the back circle through 80°, so that the deflector may be 40° on the other side of the apparent dip. Move the needle by the bracket, so that it may be deflected on the opposite side of the apparent dip to what it was before, and make three observations. The mean of the six observations or twelve readings is the apparent inclination with a deflector, face East.

Instead of placing the deflector at 40°, another angle, as 45° or 50°, may be taken; or a second angle may be used for the purpose of varying the observations when it may be desired to repeat them; the only essential point being, that the angle at which the deflector is placed should be the same on each side the apparent dip.

Instead of deflector N (or the North pole of a second needle used as a deflector), deflector S (or the South pole of the second needle) may be screwed into the opposite point of the back circle, and six observations taken with it will give as before the apparent inclination with a deflector, face East.

In writing down the observations the following directions must be attended to; if the needle be deflected past the *vertical*, the division of the limb should be read off according to the graduation and noted accordingly, but the mean of the readings must be taken from 180°, in order to give the true arc corresponding to the position of the needle: if it be deflected past the *horizontal*, the readings must be entered as marked on the limb, but with the negative sign prefixed, in which case the mean result will be half the *difference* of the means of the negative and positive readings.

The apparent inclination obtained as above directed, whether by the direct method or with deflectors, requires two corrections to give the true inclination, viz.—1° the index-correction of the particular needle employed, and 2° a correction for the influence of the ship's iron de-

pendent on the direction of her head at the time of observation. The mode of obtaining these corrections will be subsequently explained.

### B.—*Intensity.*

3. *With Weights.*—The instrument being on the gimball table and levelled, the plane of the circle parallel to the magnetic meridian, with its face to the East, and the needle shewing the magnetic dip, place the silk carrying the hooks on the grooved wheel; attach one of the constant weights to one of the hooks, and take three readings of the division of the limb at which the needle is in equilibrium, using the precautions already directed of altering the points of support of the axle between each observation, and rubbing with the ivory disk whilst reading off.

If the needle is deflected past the vertical or horizontal, read and enter the angles as already directed under the head of Inclination.

Change the weight to the other hook, when the needle will be deflected to the opposite side of the apparent dip to what it was before, and take three more observations. Half the difference of the mean of the arcs with the weight on either hook is the angle of deflection due to the constant weight employed; or half their *sum*, if one of the arcs was past the horizontal and has therefore the negative sign prefixed.

4. *With Deflectors.*—The instrument being adjusted as already described (and without using the hooks, which are only designed for the observations in which the weights are used), adjust the circle at the back by means of its verniers to the apparent dip, so that the deflectors, when screwed in, may coincide with the line of the dip; the needle will then be repelled to one side; make three observations of the division to which the needle is thus deflected, observing the usual precautions of moving the bracket at the back, reading both ends of the needle, and rubbing with the ivory disk.

Move the needle past the deflector to the other side of the dip by means of the bracket, and take three more observations: if the needle is deflected past the vertical or horizontal, read and enter the angles in the manner already described; half the difference of the arcs on either side of the apparent dip, or half their sum if one be past the horizontal and have the negative sign, will be the angle of deflection produced by the deflector. Instead of the deflectors a second needle may be used as a deflector, either with the end of the needle-case marked N (containing the north pole of the needle) screwed into the arm marked N, or the end marked S screwed into the arm marked S.

The thermometer attached to the circle must be observed at the commencement and close of the observations of intensity, whether with deflectors or weights.

A convenient routine of the observations at sea may be stated as follows:—

1. Take three observations of the apparent dip by the direct observation.

2. Screw in the deflectors N and S, and adjust the back circle to the dip. Make three observations of the angle of deflection produced on either side of the apparent dip; this furnishes one result for the intensity of the magnetic force.

3. Repeat No. 2 with a second needle used as deflector N, which will give a second result for the intensity of the force.

4. Repeat No. 2 with the second needle used as deflector S, which will give a third result for the intensity of the force.

5. Remove the deflector and repeat No. 1, which will give a second result for the apparent inclination.

On days when the weather permits, observe the intensity also by the constant weights.

### III.—Observations on Shore.

1. The instrument being adjusted with the plane of the circle coinciding with the magnetic meridian, and the face East, make a complete series of observations of the Inclination with and without deflectors, and of the Intensity with the deflectors and weights, similar in all respects to the observations which have been or which are intended to be made at sea; the needle, deflectors, and weights to be those employed, or to be employed, in the sea-observations.

2. If unfurnished with a separate apparatus for determining the true inclination, substitute in Mr. Fox's apparatus the needle which admits of its poles being reversed (viz. that needle which is not intended to be used in observations of intensity), and obtain the true inclination from the mean of the angles read in four different positions of the instrument, viz. with the face of the circle East and West, and repeating the process with the poles reversed, following the directions for reversing the poles given in Appendix 3. The difference between the true inclination thus obtained, and the apparent inclination with the face East observed with the needle used at sea, ascertained at the several shore stations, furnish one of the data from which the index correction to be applied to the observations made at sea is to be computed.

3. When Mr. Fox's apparatus is furnished with more than one needle for the observations of intensity, each needle must be successively substituted in the shore observations for the needle used at sea, and the inclination as well as the angles of deflection with constant weights observed with it.

## APPENDIX No. 3.

### Observations of the Inclination, with Barrow's Circle furnished with Microscopes and Verniers.

1. Place the instrument on a tripod stand, and level it by means of the foot-screws; then bring the vertical circle into the magnetic meridian by the following process:—Place the needle designed for the observation of the dip on the agate supports, with the side of the needle on which the letters are inscribed facing the microscopes. Turn the vernier plate so that the microscopes may be nearly in a vertical line; clamp the plate, and set the lower vernier to 90° by the tangent screw. Turn the vertical circle in azimuth, so that its face may be towards the South, and until the North pole of the needle is bisected by the wire of the microscope; raise the Ys and lower gently; if the bisection of the needle has been altered, correct by turning the circle in azimuth. Clamp the horizontal circle, and read off its vernier, calling the reading A. Now set the upper vernier to 90°, unclamp the horizontal circle, and move in azimuth (if required) until the South pole of the needle is bisected by the wire of the upper microscope. Raise the Ys and lower gently; correct the bisection (if necessary) by moving the circle in azimuth; clamp the horizontal circle and read its vernier, calling the reading B. Now unclamp the horizontal circle, and turn the vertical circle 180° in azimuth, so that its face (by which is meant the side on which the microscopes are) which was before to the South may now be to the North. Repeat the process described above, which will give two other readings of the vernier of the horizontal circle, which call C and D. Then

$$\frac{A + B + C + D}{4} = E,$$

the division of the horizontal circle to which the vernier should be set, in order that the plane of the vertical circle may be at *right angles* to the magnetic meridian; therefore, when the vernier is set to $90 \pm E$, the plane of the vertical circle will coincide with the magnetic meridian.

2. The vertical circle being now placed in the magnetic meridian, with its face to the *East*, the needle will direct itself approximately to the inclination; raise it by the Ys and lower it gently on its supports; bring the lower microscope to bisect the North end of the needle, clamp and adjust exactly by the tangent screw, read off the vernier, which will be *Face East, North End.* By means of the tangent screw of the vernier-plate bring the upper microscope to bisect the South end of the needle,

and read its vernier, which will be *face East, South end;* raise the Ys and lower gently; repeat the readings, commencing now with the South end. The mean of the four readings is the inclination with the face *East, poles direct*, or $\theta_1$.

3. Turn the vertical circle 180° in azimuth, and repeat the process in No. 2, taking again the mean of the four readings, which will be $180^\circ - \theta_2$; $\theta_2$ being the inclination with the face *West, poles direct.*

4. The poles of the needle must now be reversed by means of the bar magnets, by the following process:—Take the needle off the agates, holding it by the end which in the preceding observations was a South pole, and which is now to be converted into a North pole; place it with the flat side (which is lettered) uppermost in the wooden frame designed to prevent any injury occurring to the axle, being careful that the end to be made a North pole is placed towards that part of the wooden frame which is marked accordingly; secure the needle by the brass centre-piece, and place the frame with one end towards the right hand and the other towards the left, and let an assistant keep it in that position. Now take the bar-magnets, one in each hand, and let the *North* pole of the bar-magnet be lowermost in the hand which is towards the end of the frame in which that end of the needle is placed which is to be made a *South* pole; and let the *South* pole of the bar-magnet in the other hand be lowermost. Draw the magnet about ten times along the flat side of the needle: the North pole of one bar-magnet being drawn along the end of the needle which is to be made a South pole; and the South pole of the other bar-magnet being drawn along the end of the needle which is to be made a North pole. The needle must then be turned over in the wooden frame, so that its other flat side may become uppermost, which must also be rubbed by the magnets ten times in the manner already described.

The bar-magnets should be held one in each hand, nearly in a vertical position, the lower ends resting on the needle; and must be drawn along the grooves in the wooden frame from near the centre to beyond the ends of the needle. When the process thus described has been gone through, it will be found, on replacing the needle on the agates, that the end which previously dipped below the horizontal line is now inclined above it.

5. The observations in Nos. 2 and 3 must now be repeated, which will give two other mean readings with the face of the circle first East and then West. These readings will be $\theta_3$ (the inclination with the face *East, poles reversed*); and $180^\circ - \theta_4$; $\theta_4$ being the inclination with the face *West, poles reversed.* Then

$$\frac{\theta_1 + \theta_2 + \theta_3 + \theta_4}{4} = \theta,$$

the true magnetic inclination at the place of observation.

6. Two such determinations will generally be found sufficient, but if the results differ from each other more than 3′ or 4′ it is desirable to repeat the observations.

7. On arriving at a new station it is always desirable to magnetise the needle afresh before the observations are commenced. It is indifferent whether an observation is commenced with the end marked A as a North or as a South pole; but it is convenient to call that state of the needle in which the end A is a South pole, and the end B a North pole, "poles direct," and *vice versâ*.

Dr. Lloyd has recently suggested a mode of employing this instrument for measuring the absolute total force in localities where the inclination approaches 90°, and where the usual method of ascertaining the total force from its horizontal component ceases to be satisfactory. It consists in deflecting the dipping-needle from its natural direction in the line of the dip by a second magnet whose magnetic moment is correctly known, placed at one or more accurately measured distances from the centre of the dipping-needle, in a line at right angles to the magnetic axis of the needle, and in observing carefully the amount of the deflections thus produced. For this purpose the vernier-plate of the inclinometer is furnished with two additional arms perpendicular to those which carry the microscopes and verniers; one of these arms is prolonged by an additional piece (removable when not in use) carrying a graduated tube in which the magnet is placed, and in which it can be fixed by binding screws, with its centre at different distances from the centre of the dipping-needle and in the same vertical plane with it. The deflecting magnet being placed in the tube, and fixed at a suitable distance from the dipping-needle, with its North pole towards the needle, and the face of the circle towards the East, the microscopes are brought to coincide with the ends of the needle in the new or deflected direction. The deflecting magnet is then also in its required position, namely, at right angles to the line joining the two extremities of the needle. The arcs are read with the precautions already described in the directions for observing the inclination. The deflecting magnet is then taken out of the tube and replaced at the same distance as before, but with its South pole towards the dipping-needle, and the arcs are again read. This double process is repeated with the vernier-plate turned nearly through a semicircle, so that the deflecting magnet is brought on the other side of the dipping-needle to that which it occupied before; the face of the circle is now turned towards the West, and the observations already described are repeated. The arcs thus obtained give four values for the angle of deflection, the arithmetical mean of which is taken as the deflection ($u$), corresponding to the distance ($r$) in decimals of a foot.

If then $m$ be the magnetic moment of the deflecting magnet, and $\phi$ the total force in absolute measure :—

$$\frac{m}{\phi} = \tfrac{1}{2} r^3 \times \sin u.$$

The Inclinometers supplied to the expeditions under Sir James Ross and Sir John Richardson are furnished with the additional apparatus for this purpose. The dipping-needles are 3·5 inches in length, and the deflecting magnets are those of 3·67 inches, belonging to the unifilar magnetometers, which also make a part of the equipment of these expeditions.

The chief practical difficulty which appears to present itself in the employment of this method consists in the small distance apart at which it is necessary to place the two magnets, viz., the deflecting magnet and the dipping-needle, in order that the angle of deflection may be of a sufficiently large amount. The angle consequently is very considerably influenced by the law according to which the free magnetism is distributed in the particular magnets, and a long process of observation and of calculation is required to eliminate this effect. The formula by which the total force is deduced becomes in effect—

$$\frac{m}{\phi} = \tfrac{1}{2} r^3 \sin u \left( \frac{1}{1 + \frac{P}{r^2} + \frac{Q}{r^4} + \frac{R}{r^6}}, \text{ &c.} \right);$$

P, Q, R, &c., being coefficients depending upon the distribution of the free magnetism in the deflecting magnet and dipping-needle, and of which the values must be determined by experiments at different distances. This process may, however, be gone through in England before the instruments are supplied to the officers, or after they are returned; it has been partially accomplished at Woolwich for the magnets supplied to the Arctic expeditions above-named. The remaining observations required for a determination by this method of the total force in localities where the dip approaches 90° present no particular difficulties, and may be made on shore or on the ice whenever the expedition is stationary for a few hours. It is necessary, however, to be very particular in observing the temperature of the deflecting magnet whenever it is employed in producing deflections, and to know very accurately its temperature coefficient at different parts of the thermometric scale; and it is also necessary to combine in some satisfactory manner the observations (described in App. 1) by which the magnetic moment of the deflecting magnet is examined, with the observations in which it is made to deflect the dipping-needle.

## APPENDIX No. 4.

OBSERVATIONS REQUIRED TO DETERMINE THE EFFECT OF THE SHIP'S IRON ON THE MAGNETIC INSTRUMENTS USED ON BOARD.

1. When the ship has got her guns, shot, and iron stores on board, and in their places, and has her boats, stanchions, and all other ironwork in the positions in which they are to remain at sea, her head must be successively placed upon each of the sixteen principal points of the compass, as indicated by the standard compass used in its proper position in the ship. When the ship is quite steady, and her head is exactly on the point on which it is first to be placed, the bearing of some distant and well-defined object must be noted by the standard compass, the distance of the object being such that the space through which the ship revolves on being swung round shall make no sensible difference in its bearing; the magnetic inclination by the direct observation with Fox's apparatus must also be noted, and the angle of deflection produced by a second needle used as deflector N, in the manner described in the directions for the observations of the magnetic force with that apparatus (§ 4, page 31),

2. Repeat these three observations (viz., the bearing by the standard compass of the distant object, the inclination, and the angle of deflection for the ratio of the force), when the ship is steady with her head placed successively upon each of the sixteen principal points.

3. Determine the *real* or *true* magnetic bearing of the distant object from the ship, by taking the standard compass to some place on shore where no iron may be near, and from whence the position of the standard compass on board and the distant object shall either be in one, or in directions exactly opposite to each other. The bearing of the distant object observed from this spot will be the true magnetic bearing, or that which the compass should have shown in each of the sixteen observations on board, had it not been for the iron in the ship. The differences between the true magnetic bearing and the successive bearings on board will show the amount of the error occasioned by the ship's iron, when the ship's head was placed on each of the sixteen points. Call the error East, or −, in the cases in which the North end of the needle is drawn to the eastward by the ship's attraction, and West, or +, when drawn to the westward. Observe also and record the magnetic inclination on shore with Fox's apparatus by the direct observation and with the face of the circle to the East, precisely as when on board, as well as the angle of deflection produced by the second needle used as deflector N.

4. The observations which have thus been detailed should be repeated

whenever the ship has so materially changed her geographical position as to have altered the magnetic inclination 30° or 40°, or whenever she has been refitted, or has undergone any other change which may have made a considerable alteration either in the amount or in the distribution of her iron. It is also particularly desirable to repeat them if the ship should be in a harbour where the inclination is very small, or where it is very large; and finally, they should be repeated without fail whenever the magnetic observations made on board a ship are brought to a termination, and before any change has been made in the iron of the ship.

5. If the positions in which the standard compass and Fox's apparatus are used on board are not very far from each other, and if there is no iron within a few feet of either of them, it will usually be found, in sailing vessels built of wood at least, that the effect of the ship's iron is the same, or very nearly so, in the two positions. To prove this, place a second compass (which, like the standard compass, has had its index error, if any, determined) in the gimball-stand of the Fox's apparatus, and observe, generally, whether the two compasses agree when the ship's head is on the different points, and especially on the points of greatest and least error.

6. When the observations thus described have been carefully made and recorded, they furnish the means of calculating approximately all the corrections required to clear the magnetic observations made on board the ship, in her successive passages from port to port, from the effect of the iron upon the needles of the standard compass and of Fox's apparatus.

The calculations for this purpose have hitherto been made at Woolwich, by formulæ derived by Mr. Archibald Smith from the fundamental equations of M. Poisson's theory, in his 'Mémoire sur les Déviations de la Boussole produites par le Fer des Vaisseaux.'

For the full understanding of these formulæ, it is necessary to read Mr. Smith's notices printed in the accounts of the magnetic observations made in the Antarctic expeditions of Sir J. C. Ross, and of Lieutenants Moore and Clerk, published in Nos. V., VI., and VIII. of the Memoirs entitled 'Contributions to Terrestrial Magnetism,' in the Philosophical Transactions; but it may be convenient to reprint here the formulæ which are of most general application. In these formulæ, symbols are used which have the following significations: $\phi$ is the total magnetic force of the earth observed on shore; $\theta$ the inclination observed on shore by Fox's apparatus; $\zeta$ the true magnetic azimuth of the ship's head counted from the magnetic North, positive when her head is West of North and negative when East; $\phi'$, $\theta'$, and $\zeta'$, are the same elements observed by the needles of the standard compass and of Fox's apparatus on board;

$\zeta' - \zeta = \delta$ is the deviation or error of the standard compass caused by the ship's iron when her head is on the point $\zeta'$; and finally A, B, C, D, E, $c$, $d$, and A′, are coefficients to be employed in calculating the corrections applicable to the magnetic observations of the declination, inclination, and force made at sea in any part of the globe.

7. For the corrections of the declination A, B, C, D, and E are required; they may be computed by the following rules: let the 32 points of the compass be numbered from 1 to 32, beginning with N. by W. = 1; N. N. W.=2, &c., and going round by S.=16, to N.=32; and let the deviations observed on the different points, when the ship is swung, be designated by $\delta$ with the number attached which shows the point to which it refers: as for example $\delta_1$ will be the deviation at N. by W.; $\delta_2$ at N. N. W.; $\delta_{16}$ at South; and $\delta_{32}$ at North. Then, if the deviation has been observed on the *sixteen* principal points, we shall have the values of $\delta$ at all the even-numbered points, as $\delta_2$, $\delta_4$, $\delta_6$, &c. to $\delta_{32}$; and of these values all those in which the North end of the needle is drawn to the westward by the ship's attraction will have the sign + prefixed: and all those in which it is drawn to the eastward the sign −; the signs must be attended to in making the additions which follow:—

$$A = \tfrac{1}{16}(\delta_2 + \delta_4 + \delta_6 \ldots\ldots\ldots + \delta_{32})$$

$$\begin{aligned} B = {} & \cdot 0478 \text{ (its log} = \overline{2}\cdot 6800) \left\{\delta_2 - \delta_{30} + \delta_{14} - \delta_{18}\right\}, \\ & + \cdot 0884 \text{ (its log} = \overline{2}\cdot 9464) \left\{\delta_4 - \delta_{28} + \delta_{12} - \delta_{20}\right\}, \\ & + \cdot 1155 \text{ (its log} = \overline{1}\cdot 0625) \left\{\delta_6 - \delta_{26} + \delta_{10} - \delta_{22}\right\}, \\ & + \tfrac{1}{8}(\delta_8 - \delta_{24}). \end{aligned}$$

$$\begin{aligned} C = {} & \cdot 1155 \text{ (its log} = \overline{1}\cdot 0625) \left\{\delta_2 + \delta_{30} - \delta_{14} - \delta_{18}\right\}, \\ & + \cdot 0884 \text{ (its log} = \overline{2}\cdot 9464) \left\{\delta_4 + \delta_{28} - \delta_{12} - \delta_{20}\right\}, \\ & + \cdot 0478 \text{ (its log} = \overline{2}\cdot 6800) \left\{\delta_6 + \delta_{26} - \delta_{10} - \delta_{22}\right\}, \\ & + \tfrac{1}{8}(\delta_{32} - \delta_{16}). \end{aligned}$$

$$\begin{aligned} D = {} & \cdot 0884 \text{ (its log} = \overline{2}\cdot 9464) \left\{\delta_2 - \delta_{30} - \delta_{14} + \delta_{18} + \right. \\ & \left. \delta_6 - \delta_{26} - \delta_{10} + \delta_{22}\right\}, \\ & + \tfrac{1}{8}\left\{\delta_4 - \delta_{28} - \delta_{12} + \delta_{20}\right\}. \end{aligned}$$

$$\begin{aligned} E = {} & \cdot 0884 \text{ (its log} = \overline{2}\cdot 9464) \left\{\delta_2 + \delta_{30} + \delta_{14} + \delta_{18} - \right. \\ & \left. \delta_6 - \delta_{10} - \delta_{22} - \delta_{26}\right\}, \\ & + \tfrac{1}{8}\left\{\delta_{32} + \delta_{16} - \delta_8 - \delta_{24}\right\}. \end{aligned}$$

If the deviations are greater than 7° or 8°, the sines of the angles of deviation should be used in the formulæ instead of the angles themselves. Where time will not allow of observations being made on the *sixteen*

principal points, they may be confined to the *eight* principal points. If those observations are carefully made, the results derived from them will have nearly equal value with the results derived from observations made on sixteen points, with the important advantage that the formulæ for calculating A, B, C, D and E become much simplified. Using the same notation as before, and $\delta_4$ $\delta_8$ $\delta_{12}$ $\delta_{16}$ $\delta_{20}$ $\delta_{24}$ $\delta_{28}$ and $\delta_{32}$ being the eight deviations observed, we have

$$A = \tfrac{1}{8}\left\{\delta_4 + \delta_8 + \delta_{12} + \delta_{16} + \delta_{20} + \delta_{24} + \delta_{28} + \delta_{32}\right\}$$

$$B = \cdot 1768 \text{ (its log} = \overline{1}\cdot 2474)\left\{\delta_4 - \delta_{28} + \delta_{12} - \delta_{20}\right\} + \tfrac{1}{4}\left\{\delta_8 - \delta_{24}\right\}$$

$$C = \cdot 1768 \text{ (its log} = \overline{1}\cdot 2474)\left\{\delta_4 + \delta_{28} - \delta_{12} - \delta_{20}\right\} + \tfrac{1}{4}\left(\delta_{32} - \delta_{16}\right)$$

$$D = \tfrac{1}{4}\left\{\delta_4 - \delta_{28} - \delta_{12} + \delta_{20}\right\}$$

$$E = \tfrac{1}{4}\left\{\delta_{32} + \delta_{16} - \delta_8 - \delta_{24}\right\}$$

The coefficients being known, the deviation on any point of the compass may be computed by the following equation :—

$$\sin \delta = A + B \sin \zeta' + C \cos \zeta' + D \sin 2\zeta' + E \cos 2\zeta'.$$

A, D, and E may be expected to remain constant, or to have the same values in whatever part of the globe the ship may be, whilst no material alteration is made in the distribution of her iron. They may, therefore, be regarded as determined, once for all, by the deviations observed when the ship is first swung, though they may possibly be obtained more exactly by taking the mean of the values obtained on all occasions when that process is repeated. B and C are variable, and depend on the dip, and also on the proportion of the iron which changes its magnetic state cotemporaneously with changes in the geographical position of the ship, to the permanently magnetic iron, or to iron of an intermediate quality to the two which have been named, and of which the magnetism is neither permanent on the one hand, nor, on the other, are its changes cotemporaneous with changes of the dip, but are consequent on such changes, and require a greater or less interval to conform to them. It is on account of the uncertainty of the law according to which these two coefficients B and C vary in different ships, that when a ship has changed considerably her geographical position, it is desirable to repeat the process by which the values of the coefficients may be re-determined; and that it is still more desirable that a full and sufficient trial should be made of a very simple method suggested by Mr. Archibald Smith, in No. VIII. of the 'Contributions to Terrestrial Magnetism,' for determining the variable coefficients at any time that may be wished, either at sea or in harbour, by deflections of the compass-needle with the ship's head successively on any two opposite

points of the compass. By the addition of a brass bar attached at right-angles to the prism and sight-vane of the azimuth ring of the standard compass, a deflecting magnet or magnets may be temporarily fixed at a convenient distance from the compass-needle, and the deflection observed with the ship's head on opposite points by a process requiring only a very few minutes, and independent of the visibility of the sun or stars, or of any distant object. If the points taken be those which the observations in harbour have shown to be points of no disturbance, and if $v_1$ $v_2$ be the angles of deflection on the respective points—

$$\sqrt{B^2 + C^2} = \frac{\sin v_1 - \sin v_2}{\sin v_1 + \sin v_2};$$

$$= \frac{\tan \frac{v_1 - v_2}{2}}{\tan \frac{v_1 + v_2}{2}},$$

and the deviations on the several points may be computed by

$$\sin \delta = A + \sqrt{B^2 + C^2} \sin (\zeta' + \alpha) + D \sin 2\zeta' + E \cos 2\zeta',$$

in which $\alpha$ is the easterly azimuth of the line of no deviation.

Should this method of determining the variable part of the correction formula be found to succeed on trial, the correction of the disturbances by the officers of a ship might be still further simplified, by the formation of tables of each term for every probable value of the coefficients, requiring merely the addition of the quantities to be taken out from the tables. In the meantime the calculations may be facilitated by the following table, extracted from Mr. Smith's Memorandum in No. VIII. of the 'Contributions to Terrestrial Magnetism.'

Let $B_1$, $B_2$, . . . . $B_7$, $C_1$, $C_2$, . . . . $C_7$ represent the values of B and C multiplied by sin 11° 15′, sin 22° 30′, &c.; and let $D_2$, $D_4$, $D_6$, $E_2$, $E_4$, $E_6$ represent the values of D and E multiplied by sin 22° 30′, sin 45°, and sin 67° 30′; we have then—

$$\delta_{32} = A + C + E$$
$$\delta_{16} = A - C + E$$

$$\delta_1 = A + B_1 + C_7 + D_2 + E_6$$
$$\delta_{31} = A - B_1 + C_7 - D_2 + E_6$$
$$\delta_{15} = A + B_1 - C_7 - D_2 + E_6$$
$$\delta_{17} = A - B_1 - C_7 + D_2 + E_6$$

$$\delta_2 = A + B_2 + C_6 + D_4 + E_4$$
$$\delta_{30} = A - B_2 + C_6 - D_4 + E_4$$
$$\delta_{14} = A + B_2 - C_6 - D_4 + E_4$$
$$\delta_{18} = A - B_2 - C_6 + D_4 + E_4$$

$$\delta_3 = A + B_3 + C_5 + D_6 + E_2$$
$$\delta_{29} = A - B_3 + C_5 - D_6 + E_2$$
$$\delta_{13} = A + B_3 - C_5 - D_6 + E_2$$
$$\delta_{19} = A - B_3 - C_5 + D_6 + E_2$$

$$\delta_4 = A + B_4 + C_4 + D$$
$$\delta_{28} = A - B_4 + C_4 - D$$
$$\delta_{12} = A + B_4 - C_4 - D$$
$$\delta_{20} = A - B_4 - C_4 + D$$

$$\delta_5 = A + B_5 + C_3 + D_6 - E_2$$
$$\delta_{27} = A - B_5 + C_3 - D_6 - E_2$$
$$\delta_{11} = A + B_5 - C_3 - D_6 - E_2$$
$$\delta_{21} = A - B_5 - C_3 + D_6 - E_2$$

$$\delta_6 = A + B_6 + C_2 + D_4 - E_4$$
$$\delta_{26} = A - B_6 + C_2 - D_4 - E_4$$
$$\delta_{10} = A + B_6 - C_2 - D_4 - E_4$$
$$\delta_{22} = A - B_6 - C_2 + D_4 - E_4$$

$$\delta_7 = A + B_7 + C_1 + D_2 - E_6$$
$$\delta_{25} = A - B_7 + C_1 - D_2 - E_6$$
$$\delta_9 = A + B_7 - C_1 - D_2 - E_6$$
$$\delta_{23} = A - B_7 - C_1 + D_2 - E_6$$

$$\delta_8 = A + B - E$$
$$\delta_{24} = A - B - E$$

If the angles are greater than 7° or 8°, these formulæ give the sines of the angles of deviation instead of the angles.

8. For the correction of the inclinations observed at sea the coefficients $c$ and $d$ may be computed from the disturbances on the several points, shown by the observations of the inclination with Fox's apparatus when the ship was swung in harbour, by the formula:—

$$c \cos \zeta + d \tan \theta = (1 - D) \sin \zeta \operatorname{cosec} \zeta' \tan \theta'$$

for all other points than North and South, and with the ship's head North or South, by—

$$c \cos \zeta + d \tan \theta = (\cos \zeta + B) \sec \zeta' \tan \theta';$$

observing that the values of $\zeta'$ employed should be calculated by the declination-coefficients. With the values of $c$ and $d$ thus obtained, tables for the correction of the inclinations observed on different courses at sea in all values of $\theta$ may be computed by the formula:—

$$\tan \theta' = \frac{c}{(1 - D)} \cdot (\cos \zeta + \frac{d}{c} \tan \theta) \sin \zeta' \operatorname{cosec} \zeta,$$

$$\text{or } \tan\theta' = c\,\frac{\cos\zeta + \dfrac{d}{c}\tan\theta}{\cos\zeta + \mathrm{B}}\,.\,\cos\zeta';$$

observing that the first must be used when the ship's course is between N. E. and S. E., or N. W. and S. W.: and the second when her course is nearer the N. and S. points; and that the values of $\zeta'$ should be calculated by means of the declination-coefficients.

9. The coefficient A′, for the correction of the intensities observed at sea, may be computed by the subjoined formulæ, from the observations of the intensity with Fox's apparatus on board with the ship's head on the different points, compared with those of the same instrument on shore, and with the absolute value of the total force on shore ($\phi$) obtained in the manner described in App. 3. Tables for the correction of the intensities observed at sea may also be constructed by the same formulæ:—

$$\frac{\phi'}{\mathrm{A}'\phi}\sin\theta' = c\cos\theta\cos\zeta + d\sin\theta,$$

$$\text{or } \frac{\phi'}{\mathrm{A}'\phi}\cos\theta'\sin\zeta' = (1-\mathrm{D})\cos\theta\sin\zeta;$$

the first to be used when the inclination is large, and the second when the inclination is small.

10. If the disturbances of the compass-needle, at the spot where the gimball-table for Fox's apparatus is fixed, differ materially from those at the spot where the standard compass is fixed, the standard compass may be removed temporarily to the gimball-table, and the deviations observed on the eight principal points, which will give the values of B and D for that spot, as well as determine the points on which there is no disturbance: if these are opposite points, the value of the variable coefficient B can always be ascertained experimentally for the correction of the observations of inclination and intensity, by the angles of deflection produced in a compass-needle placed on the gimball-table by the method described in 7, p. 8.

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